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著者	石黒 章夫
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Adaptive Reconfiguration of a Modular Robot through Heterogeneous Inter-Module Connections

Masahiro Shimizu, Takuma Kato, Max Lungarella and Akio Ishiguro

Abstract— **Modular robots are mechatronic systems that can rearrange their connectivity to create new topologies to accomplish diverse tasks. In previous work, we have studied a modular reconfigurable robot (Slimebot) characterized by a spontaneous inter-module connection control mechanism. The modules of Slimebot connect to each other via a functional material which satisfies physical coupling between the ones. Here, we investigate the effect of heterogeneous inter-module coupling strengths on the adaptivity of Slimebot (here measured in terms of structural stability and locomotive speed). Simulation results show that a certain amount of heterogeneity improves the adaptivity of the system compared to the case of homogeneous modules. The only assumption that needs to be satisfied by the system with heterogeneous couplings is compliance to Steinberg's energy minimization theory.**

I. INTRODUCTION

Modular (or self-reconfigurable) robots are robotic systems composed of a variable number of (typically identical) mechanical units (modules) [1], [2], [3], [4]. A number of characteristics make modular robots attractive alternatives to robots with a fixed structure. Modular robots are by design versatile and can (at least theoretically) adapt to different tasks in different environments, *e.g.*, by changing their shape. They can be mass produced for vast cost savings (due to economy of scale), they display graceful degradation (the functionality is preserved in the face of damage), and are intrinsically scalable (modules can be added easily). These characteristics resemble those of some biological systems. Despite their appealing nature, creating reconfigurable robot systems poses many scientific and engineering challenges. In the context of this paper two such challenges are of particular relevance. The first one concerns inter-module connection control. Individual modules typically connect among themselves by means of either mechanical or electromagnetic connectors. One disadvantage of such inter-module connections is that because they need be carefully designed to minimize play and maximize rigidity, they lack flexibility and robustness against environmental perturbations [5]. Moreover, although most "rigid" mechanisms guarantee controllability and a certain degree of stability, the control algorithms involved are computationally expensive and sometimes even intractable [6]. The second issue addressed concerns the homogeneity (or, unit-modularity [7]) of most extant modular robots which consist of identical units. Although this condition is important for economy of scale, it is not practical in the real world. Most useful robots do not only need specialized parts (*e.g.*, specific sensors, actuators, and tools), but in order to reduce the production costs some tolerance needs to be allowed during the manufacturing process. Moreover, when modules will be further miniaturized fewer components will fit on each module leading quite naturally to less homogeneous designs [7].

M. Shimizu is with the Deptartment of Electrical and Communication Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan shimizu@cmplx.ecei.tohoku.ac.jp

T. Kato is with the Deptartment of Electrical and Communication Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan kato@cmplx.ecei.tohoku.ac.jp

M. Lungarella is with the Artificial Intellience Laboratory, University of Zurich, 8050 Zurich, Switzerland lunga@ifi.uzh.ch

A. Ishiguro is with the Deptartment of Electrical and Communication Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan ishiguro@ecei.tohoku.ac.jp

Here, we relax the rigidity and the homogeneity assumptions by considering a system in which the connectivity control is "loose" and in which a certain amount of heterogeneity is allowed. We use the modular robot Slimebot [8] as an instance of a robot for which the configuration can be altered actively through environmental interaction. Interestingly, global coordination and a primitive form of goal-oriented behavior are achieved without the need of a central controller but through local interaction dynamics only. It is thus plausible to assume that the characteristics and the global behavior of Slimebot strongly depend on how its modules are coupled.

The goal of this paper is to investigate the effect of heterogeneous coupling strengths (adhesiveness) on the adaptivity of modular robots. In what follows, we first measure the degree of adaptivity of a homogeneous Slimebot as a function of the adhesiveness between modules. Second, we evaluate the performance of the system as a function of the number of modules connected to form a cluster. Then, we introduce the notion of heterogeneous inter-module adhesiveness, and compare homogeneous and heterogeneous systems in terms of adaptivity. Finally, we discuss the significance of the initial spatial distribution of modules in the case of heterogeneous systems, and motivate our choices using Steinberg's energy minimization theory. Our results indicate that Slimebot seems to be an adequate tool for testing ideas on how modular systems could exploit processes of self-organization and display emergent (not planned) functionality.

II. SLIMEBOT: DESCRIPTION AND FUNCTION

In this section, we describe the mechanical structure and the distributed control algorithm of Slimebot. We then give an example of its functioning and show that Slimebot locomotes through repeated connections and disconnections between the modules.

A. Mechanical Structure

We first consider a two-dimensional (homogeneous) Slimebot consisting of many identical modules (Fig. 1, left), each of which has a mechanical structure shown in Fig. 1 (right). Each module is equipped with a ground friction control mechanism (explained later), an omnidirectional light sensor, and six telescopic arms actuated by linear motors. For attachment to other modules, the circumference of the module is covered by a "functional" material. More specifically, we use a genderless Velcro strap: when two halves of Velcro come into contact, they easily stick together; however, when a force greater than the Velcro's yield strength is applied, the halves automatically separate. We expect that by exploiting the properties of Velcro, a spontaneous connection control mechanism is realized which not only reduces the computational cost required for the connection control, but also allows to harness emergence to achieve more adaptivity (*e.g.*, resilience towards external perturbations). We also assume that local communication between connected modules is possible. Such communication will be used to create a phase gradient inside the modular robot (discussed below). In this study, each module is moved by the telescopic actions of the arms and by ground friction. Note that the individual modules do not have any mobility but can only move by "cooperating" with other modules.

B. Control Algorithm

In this section, we discuss how the mechanical structure described above can generate stable and continuous locomotive patterns. To this end, each module is endowed with a nonlinear oscillator. Through mutual entrainment (frequency locking) among the oscillators, rhythmic and coherent locomotion is produced. In what follows, we give a detailed explanation of this algorithm.

1) Active Mode and Passive Mode: At any time, each module in the Slimebot can take one of two mutually exclusive modes: it can be either active or passive. As shown in Fig. 2, a module in the active mode contracts or extends its telescopic arms while simultaneously reducing its ground friction. By contrast, a module in the passive mode increases its ground friction, and returns its arms to their original position. Note that a module in the passive mode does not move on its own, but – when in active mode – cooperates with the neighboring (locally-interacting) modules to achieve efficient movement of the entire modular system.

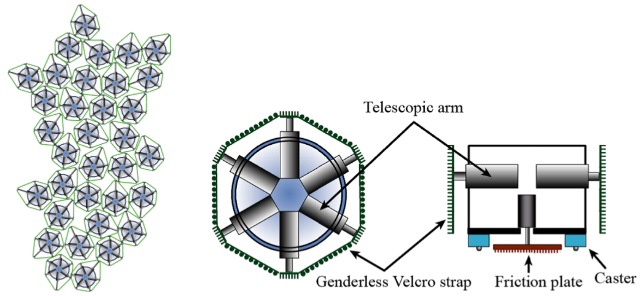

Fig. 1. Schematics of Slimebot. (left) Entire system. (right) Mechanical structure of each module; top view, and side view.

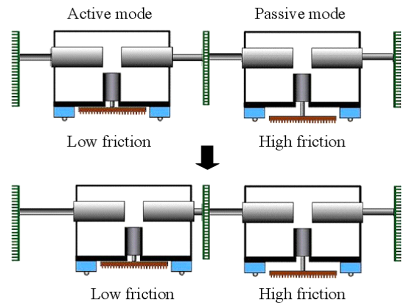

Fig. 2. Schematic of the active mode and the passive mode. A module in the passive mode sticks to the ground and acts as a supporting point. Side view of the connected modules is shown for clarity.

2) Phase Gradient through Mutual Entrainment: In order to generate rhythmic and coherent locomotion, the mode alternation in each module should be controlled appropriately. Of course, such control should be decentralized, and should be independent of the number of modules or the morphology of the Slimebot. To do so, we focus on the *phase gradient* created by the mutual entrainment of locally-interacting nonlinear oscillators in the Slimebot, by exploiting it for the mode alternation. Therefore, the configuration of the resulting phase gradient is extremely important.

As a model of a nonlinear oscillator, we employ the *van der Pol oscillator* (hereinafter VDP oscillator) – an oscillator widely used due to its entrainment property. The equation of the VDP oscillator implemented on module i is given by

$$\alpha_i \ddot{x}_i - \beta_i (1 - x_i^2)\dot{x}_i + x_i = 0, \tag{1}$$

where x_i is the state of the oscillator at time t, α_i specifies the frequency of the oscillation, and β_i is the convergence rate to the limit cycle. The local communication among physically connected modules is realized by the mutual interaction of the VDP oscillators of these modules, and can be expressed as:

$$x_i = x_i^{\mathrm{tmp}} + \varepsilon \left\{ \frac{1}{N_i(t)} \sum_{j=1}^{N_i(t)} x_j^{\mathrm{tmp}} - x_i^{\mathrm{tmp}} \right\}, \tag{2}$$

where x_i^{tmp} is the state before the local interaction, and $N_i(t)$ is the number of neighbors of module i at time t. The parameter ε specifies the strength of the interaction. Note that this local interaction acts like a diffusion.

When the VDP oscillators interact according to Eq. (2), a phase distribution can be effectively created by varying the value of α_i in Eq. (1) for some of the oscillators. In order to create an equiphase surface effective for generating locomotion, we set the value of α_i as:

$$\alpha_i = \begin{cases} 0.7 & \text{if the goal light is detected} \\ 1.3 & \text{if the module is outer surface} \\ 1.0 & \text{otherwise} \end{cases} \tag{3}$$

Note that except the modules detecting the goal light, the modules on the boundary, *i.e.*, the outer surface of the

Slimebot, have the value of $\alpha_i = 1.3$. This allows us to introduce an effect akin to surface tension (which in water is caused by the attraction between H_2O-molecules) that is indispensable to maintain the coherence of the entire system (see below).

3) Amoebic Locomotion: We consider a control algorithm that exploits the phase distribution created by the mutual entrainment among the VDP oscillators. To do so, the two possible modes, *i.e.*, the active and passive modes, of each module are altered according to the phase distribution that emerges. The timings of the mode alternation are propagated from the front to the rear of the modular robot as traveling waves. In this study, the extension/contraction of each arm of module i in the active mode is determined according to the phase difference with its corresponding neighboring module. Due to this, the degree of arm extension/contraction of each module will become most significant along the phase gradient, enabling the entire system to move towards a light source while maintaining its coherency.

C. Assessing Adaptive Behavior

1) Problem Setting: We adopt *phototaxis behavior* as a practical example. The task of Slimebot is to move towards a light source (goal) while maintaining its structural coherence in the face of external perturbations (obstacles). In the simulation discussed below, the goal is located at the top of the figure, and the Slimebot thus locomotes upwards.

2) Simulation Results: Representative results obtained for a Slimebot consisting of 500 modules are shown in Fig. 3. These snapshots are in the order of the time transition. As evident from the figure, the Slimebot can successfully negotiate the environmental perturbations without losing its coherence. At least two points are noteworthy. First, the traveling wave stemming from the phase distribution created through the mutual entrainment gradually becomes conspicuous ($t = 1000$), and the right and left outer sections in the module group start moving towards the center. As a result, locomotion is generated through repeated connections and disconnections among the modules. It should be noted that the dynamics of the spontaneous connection control mechanism provided by the functional material is fully exploited in the process. Second, the Slimebot negotiates its environment by enclosing the obstacles. Note that this behavior is not pre-programmed, but is totally emergent.

3) Experimental Result: One of the most important features expected in the Slimebot is adaptive reconfiguration by fully exploiting the spontaneous connection control mechanism provided by the genderless Velcro strap. In order to verify this feature, we have studied how a real world implementation of Slimebot negotiates the environment containing obstacles. Fig. 4 depicts the experimental result with a Slimebot consisting of 17 modules. Interestingly, the Slimebot selected the specific route (right side of the obstacle) for obstacle avoidance with adaptive reconfiguration. Let us emphasize that both experimental and simulation results indicate that Slimebot's adaptive behavior is totally emergent from the interactions among the control system (*i.e.*, the mutual entrainment among the nonlinear oscillators), the mechanical system (*i.e.*, mechanical interactions among the modules via the Velcro straps) and the environment.

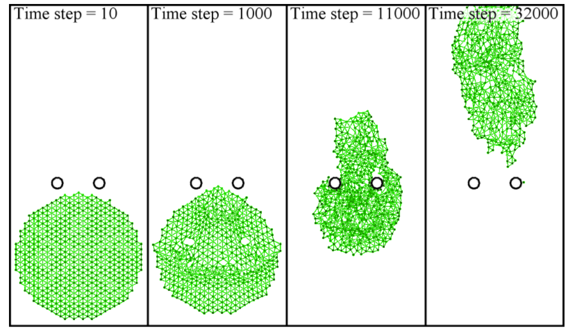

Fig. 3. Representative data of the transition of the morphology in the case of 500 modules. The thick circles in the figures are the obstacles. Note that no active control mechanism that precisely specifies connection/disconnection among the modules is implemented. Instead, a spontaneous connectivity control mechanism exploiting a functional material, *i.e.*, genderless Velcro strap, is employed.

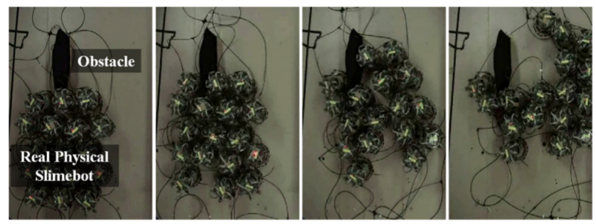

Fig. 4. Adaptive reconfiguration with 17 modules. From left to right: Sequence of snapshots of a typical example of a spontaneous inter-module connection control.

D. Coherence as a function of the number of connected modules

As stated above, the degree of coherence of Slimebot is due to an effect similar to surface tension. The effect is induced by the phase gradient generated through the mutual entrainment among the modules. Mutual entrainment, in turn, occurrs when a certain number of modules is connected to form a cluster (see insets in Fig. 5). It follows that the degree of coherence is a function of the size of the cluster. We studied the resulting relationship using the following procedure: 1) A Slimebot consisting of a given number of modules is initialized in an environment devoid of obstacles and goal lights; 2) a constant force is applied to two modules at the boundary in such a way that the force destroys the "swarming configuration" of Slimebot and thus its coherence; 3) the period during which the system maintains coherence was recorded; 4) the number of physically connected modules is increased and the experiment is repeated.

Fig. 5 depicts the results of our simulation (the data represent averages over 20 experimental runs). In each run the Slimebot had a different overall shape. As can be seen in the figure, a sharp increase of performance (i.e. degree coherence) occurs when more than 10 modules form a connected aggregate (i.e. the size of the cluster is bigger than 10 modules). When the number of connected modules is lower than 10, every module becomes a "boundary" module.

Thus, no phase gradient is induced with a consequent loss of coherence. By contrast, in the region with more than 10 modules, the swarm displays coherence and a phase gradient is produced as a consequence of the surface tension. These results are in good agreement with the definition of Swarm Intelligence given in [9].

III. EFFECT OF HETEROGENEOUS INTER-MODULE ADHESIVENESS ON ADAPTIVITY

To shed some light on the origin and nature of Slimebot's adaptive behavior, it is important to better understand the spontaneous connection control mechanism; in particular, because the physical connection network of modules directly (and causally) affects the control system network (the network of coupled VDP oscillators embedded in each module). Thus, we introduce heterogeneity into the connectivity mechanism of each module and study how the spontaneous connectivity control mechanism affects Slimebot's adaptive behavior. More specifically, we estimate its effect on adaptivity by comparing the homogeneous Slimebot (composed of identical modules) with the heterogeneous Slimebot (composed of two types of modules, *i.e.*, modules surrounded by a "weak" and by a "strong" Velcro strap).

A. *Evaluating Adaptivity*

To assess the effect of heterogeneous inter-module connections on the robot's adaptivity, we define an index of performance (evaluation function). We note that the Slimebot has to satisfy the following two *ambivalent* criteria: (1) maintain the coherence of the entire system (structural stability); and (2) be capable of self-reconfiguration via connection/disconnection of modules. Both criteria should be satisfied (at least to a certain degree) at all times. This leads to the following evaluation function:

$$\mathrm{Eval} = e_c \cdot e_v \tag{4}$$

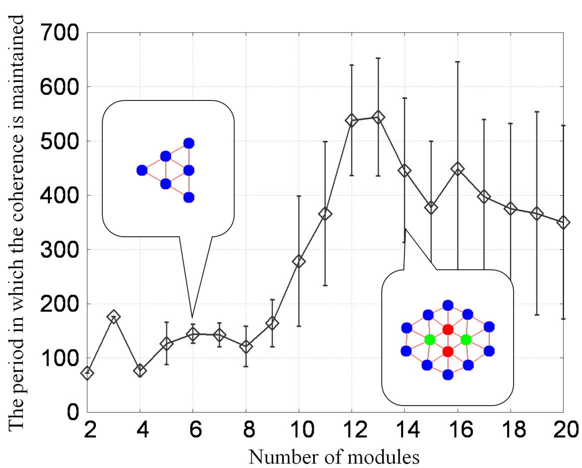

Fig. 5. Effect of surface tension on Slimebot's coherence as a function of the number of modules composing a cluster. A constant force is continuously applied to the Slimebot's boundary modules until it disintegrates. Then, the period, in which the coherence is maintained, is measured. Note the elbow when the number of modules is 10.

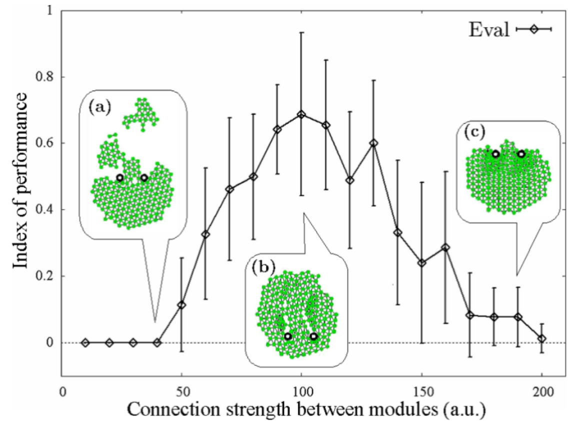

Fig. 6. Relationship between the connection strength and the index of performance.

where e_c is a scalar proportional to the coherence of the Slimebot, and e_v reflects how well the robot satisfies criterion 2 (e_v is essentially a scalar proportional to the average module speed, *i.e.*, the faster the Slimebot the better). In other words, the evaluation function $Eval$ returns a higher value if both e_v and e_c are simultaneously satisfied, that is, if the robot moves faster while maintaining its coherence. We note that the evaluation function is normalized to lie in $[0, 1]$. To explain this, the detailed expression of e_c and e_v are written as follows:

$$e_c = \begin{cases} a_c(-c + c_0) & (c \leq c_0) \\ 0 & (c > c_0) \end{cases} \tag{5}$$

$$e_v = a_v(v_g - v_0) \tag{6}$$

where c_0 and v_0 are the offset constant for appropriate evaluation; a_c and a_v are constants for normalization; c is number of clustered swarm; and v_g is the velocity of the center of gravity of Slimebot. Here, the coherency of Slimebot is defined based on Eq. (5) in such a way that the c more than c_0 makes the evaluation of coherency 0. That is to say, if c is 1, the evaluation of coherency becomes the highest value.

B. *Simulation Results*

We carry out simulations in order to estimate the effect of the heterogeneity on Slimebot's adaptivity. To this end, we first assess the degree of adaptivity in the case of a homogeneous Slimebot (identical inter-module connections). Then, we study the case of a heterogeneous Slimebot.

1) Homogeneous Slimebot: We estimate the degree of adaptivity based on Eq. (4) with respect to the connection strength between modules. In this simulation, the number of modules is set to 200. The task of the Slimebot is to move towards a location marked by a light-emitting source and somehow negotiate two circular obstacles. The index of performance as a function of the connection strength is visualized in Fig. 6. As the figure shows, the degree of adaptivity strongly depends on the connection strength between the modules. The evaluation function takes a low value for either too weak or too strong Velcro strap. For intermediate values of the connection strength, however, the homogeneous Slimebot satisfies the aforementioned ambivalent criteria and successfully negotiates the environment.

2) Heterogeneous Slimebot: In the case of the homogeneous Slimebot, we find that the degree of adaptivity ($Eval$) correlates strongly with the connection strength between the modules. We hypothesize that each value of the inter-module connection strength is tuned to a particular environment (which is characterized by a particular disposition of obstacles, with a particular size or shape, and so on). We thus expect that a heterogeneous connection mechanism should lead to an increase of the adaptivity of the Slimebot because such a robot should be able to handle different kinds of environments.

As the first step towards addressing the issue, we assume the simplest possible heterogeneous connection strength distribution inside the Slimebot. That is, the distribution consists of only two types of connection strengths which are randomly assigned to the inner modules of the Slimebot.

In order to quantify the effect of heterogeneous inter-module connections, we estimate the degree of adaptivity in the same condition as for the homogeneous Slimebot (Fig. 6). The result obtained is shown in Fig. 7. We note that the diagonal of the matrix represent the result obtained for the homogeneous Slimebot (Fig. 6). Interestingly, for specific combinations of the Velcro strength (*e.g.*, $80, 120$), the heterogeneous Slimebot shows higher adaptivity than the homogeneous one. In other words, the highest value of the evaluation function (4) is observed for heterogeneous inter-module connections. Note also that in the heterogeneous case too weak or strong a connection strength leads to lower adaptivity (when compared to the homogeneous case). From these results we further imply that the initial spatial distribution of the heterogeneity plays an important role. We elaborate on this point in the following section.

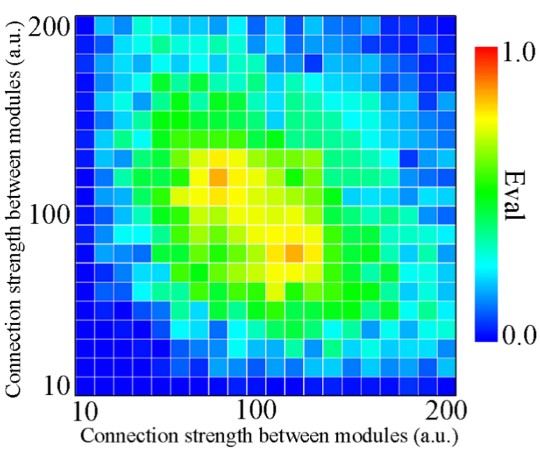

Fig. 7. Performance of the heterogeneous inter-module connection mechanism. The horizontal and vertical axes indicate the connection strength between modules. The colors show the degree of adaptation on the matrix of connection strength combination.

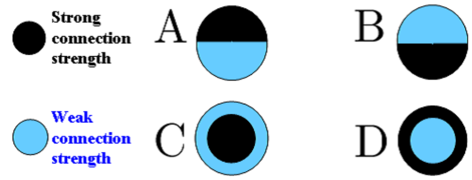

Fig. 8. Initial coupling strength distributions used for assessing the role of spatial structure on adaptivity. The initial arrangement of the modules is circular.

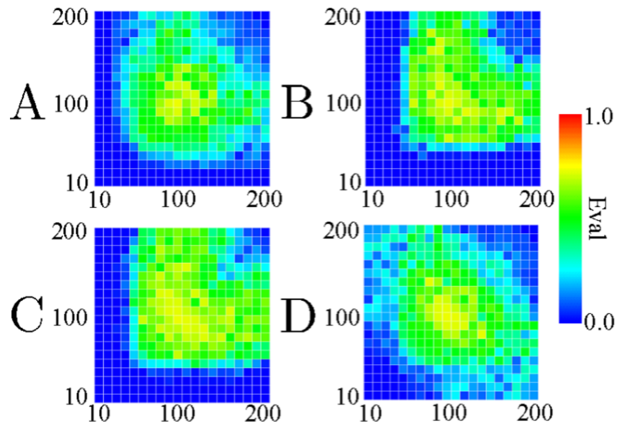

Fig. 9. Performance indexes as a function of the connection strength and of the spatial distribution of the connection strengths.

IV. DISCUSSION

In this section, we discuss three issues. First, we elaborate on the significance of the spatial structure of the heterogeneity. Then, we show that "adaptive" initial module distributions are thermodynamically plausible and are justifiable through Steinberg's energy minimization theory.

A. Spatial Structure and Heterogeneity

In Section 3, the heterogeneous Slimebot showed a higher adaptivity than the homogeneous one if the connection strengths are adequately chosen. However, this result should be related to the spatial structure of the heterogeneous connection strength distribution inside the Slimebot. We have thus measured the adaptivity of the heterogeneous Slimebot for four different initial spatial distributions of the inter-module coupling strengths (Fig. 8). Figure 9 indicates the corresponding simulation results. As the latter figure shows, for all the spatial structures, the highest value of the evaluation function $Eval$ does not exceed the one obtained for a random initial distribution (see Section 3B). Even if this is only a preliminary result, and we will need to perform a more extensive analysis, it clearly indicates that the spatial distribution of the heterogeneity (its spatial structure) plays a crucial role.

B. Steinberg's Thermodynamic Model

In the previous section, we have given some results indicating how the initial spatial distribution of the heterogeneity affects adaptivity. However, we have not mentioned which criterion we used for initializing the distributions of Slimebot modules. In this study, the specification of the distribution is governed by Steinberg's thermodynamic model [10], [11]. Steinberg proposed an energy minimization theory – the differential adhesion hypothesis – to explain cell division, cell sorting, and self-assembly processes in tissues. He showed that differences in the intercellular adhesiveness can dramatically affect the final configuration of an organism (Fig. 10). Inspired by this remarkable idea, we investigate how the equilibrium configuration can be altered by different coupling strengths. For simplicity, we employ a Slimebot consisting of two types of modules (A and B), each with its own specific module-to-module adhesiveness. For convenience, let the connection strength between two modules A be W_{AA}, the one between B modules be W_{BB}, and the one between an A module and a B module be W_{AB}. That is, in Section 3, the distribution consisting of two types of modules with different coupling strengths is governed by the following condition:

$$W_{\rm AB} > W_{\rm AA} = W_{\rm BB}. \quad (7)$$

This relationship leads to randomly distributed couplings inside the Slimebot (Fig. 11).

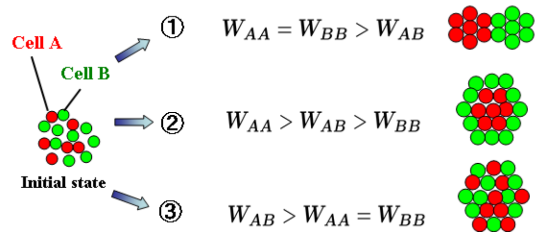

Fig. 10. The three conditions of Steinberg's thermodynamic model.

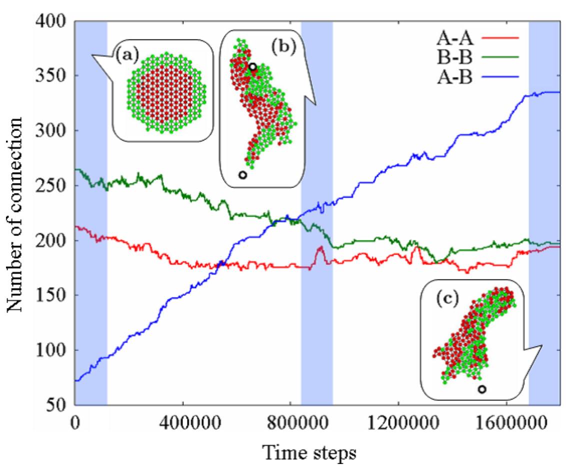

Fig. 11. Time evolution of the number of connection among module types. At all times, $W_{AB} > W_{AA} = W_{BB}$. The Slimebot depicted at each gray region shows the characteristic shape at the moment.

V. CONCLUSION

In this paper, we studied the effect of heterogeneous coupling strengths on the adaptivity of modular robots. We showed that a certain amount of heterogeneity improves the adaptivity of the system compared to the case of homogeneous modules. The only condition that needs to be satisfied by the system with heterogeneous couplings is compliance to Steinberg's thermodynamic model for tissues. Our results indicate that a certain amount of heterogeneity may lead to more "ecologically balanced" systems [12]. As shown in the simulation results, inappropriate heterogeneity leads to "unbalanced behavior" and loss of adaptivity (*e.g.*, disintegration of the swarm in the case of a too weak adhesiveness combination). However, appropriate heterogeneity enhances the system's adaptivity. In conclusion, heterogeneity affects not only the physical connectivity of the system (its topological structure), but influences also the robot's control system and behavior (its functionality). Structure and function are therefore, once more, discovered to be inseparable and tightly intertwined, their interaction being also influenced by the system size (*i.e.*, number of connected modules). Although, we analyzed this issue only in the case of homogeneous modules, our results seem to be consistent with the definition of Swarm Intelligence given in [9]. Future work will be devoted to extend the analysis to a system with heterogeneous inter-module connections.

ACKNOWLEDGMENTS

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